

Summary of the XXVIIth Rencontres de Blois: Particle Physics and Cosmology

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This writeup summarises some of the highlights from the 2015 Rencontres de Blois, with a compression ratio of about 100:1 relative to the original presentations.

1 Introduction

The XXVIIth Rencontres de Blois has taken place at a special moment in particle physics and cosmology, one where it is a privilege to take stock of the shape of the fields of particle physics and cosmology: nearly all results from Run 1 of the Large Hadron Collider have now emerged, the Planck experiment has released many of its main findings and there is also a wealth of data from cosmic-ray experiments. At the same time, we can look forward to Run 2 of the LHC, which started as the conference was taking place, and much progress in the near future also in dark matter searches.

This summary selects a few of the highlights from the roughly 130 talks of the conference (mostly the 31 plenary talks), with the perspective of a particle physicist, but attempting to reflect the roughly 1:1 balance of LHC and non-LHC subjects. The selection is woefully incomplete, and the reader is referred to the complete proceedings for the details of the many subjects that were touched upon.

2 Higgs, top and other standard-model physics

The widely celebrated major achievement of Run I of the LHC was the discovery of the Higgs boson. The Higgs boson comes late to the stable of standard-model particles. At least in part, this is a consequence of its rather low production cross section, which is an order of magnitude smaller, say, than the $t\bar{t}$ cross section in 8 TeV proton-proton collisions at the LHC.

We have, however, been exceptionally lucky with the mass of the Higgs boson. At 125 GeV, a wide range of its decays have already proved amenable to some degree of study, including those to $\gamma\gamma$, ZZ^* , WW^* , $\tau^+\tau^-$, $b\bar{b}$. Thanks to the decays to $\gamma\gamma$ and ZZ^* , it is possible to measure its mass precisely: though barely 3-years have passed since discovery, the 0.2% precision obtained on the Higgs mass,^{1,2} Fig. 1 (left), already surpasses the roughly 0.4% that is typically quoted for the top-quark mass³. The data are also clearly consistent with a 0^+ spin-parity assignment.

As illustrated in Fig. 2, the overall rate of Higgs production has been constrained at the level of about 15% and a number of its branching ratios have been determined with precisions in the range of 20 – 40% (modulo an overall normalisation). There are even first constraints on its total width. The data have been analysed in myriad other ways, one of the most common being the extraction of “ κ -factors”: e.g. one allows for a rescaling of all vector couplings by a factor κ_V and all fermion couplings by κ_F and attempts to determine the allowed range of κ_V, κ_F values.

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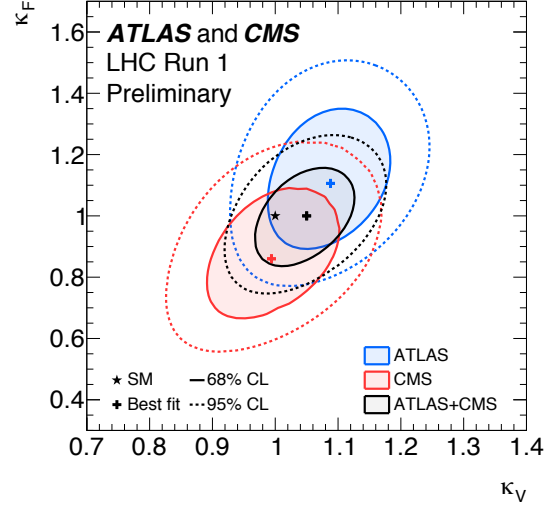
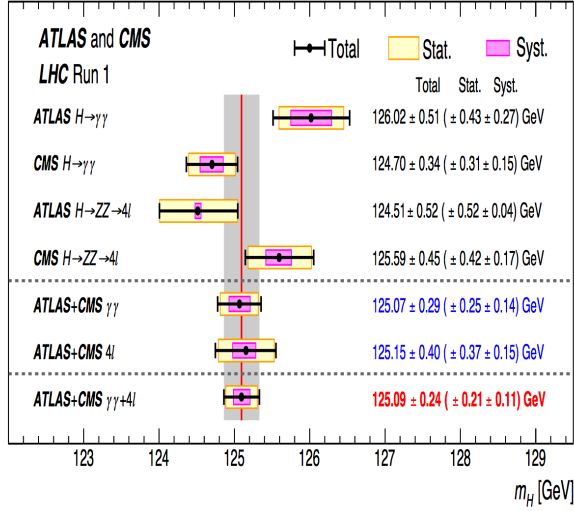


Figure 1 – Left: combined ATLAS and CMS Higgs boson mass measurements (figure from the talk by Gomez²). Right: joint ATLAS and CMS fit for the scaling factors κ_F and κ_V that multiply the fermionic and vector couplings of the Higgs boson.⁴

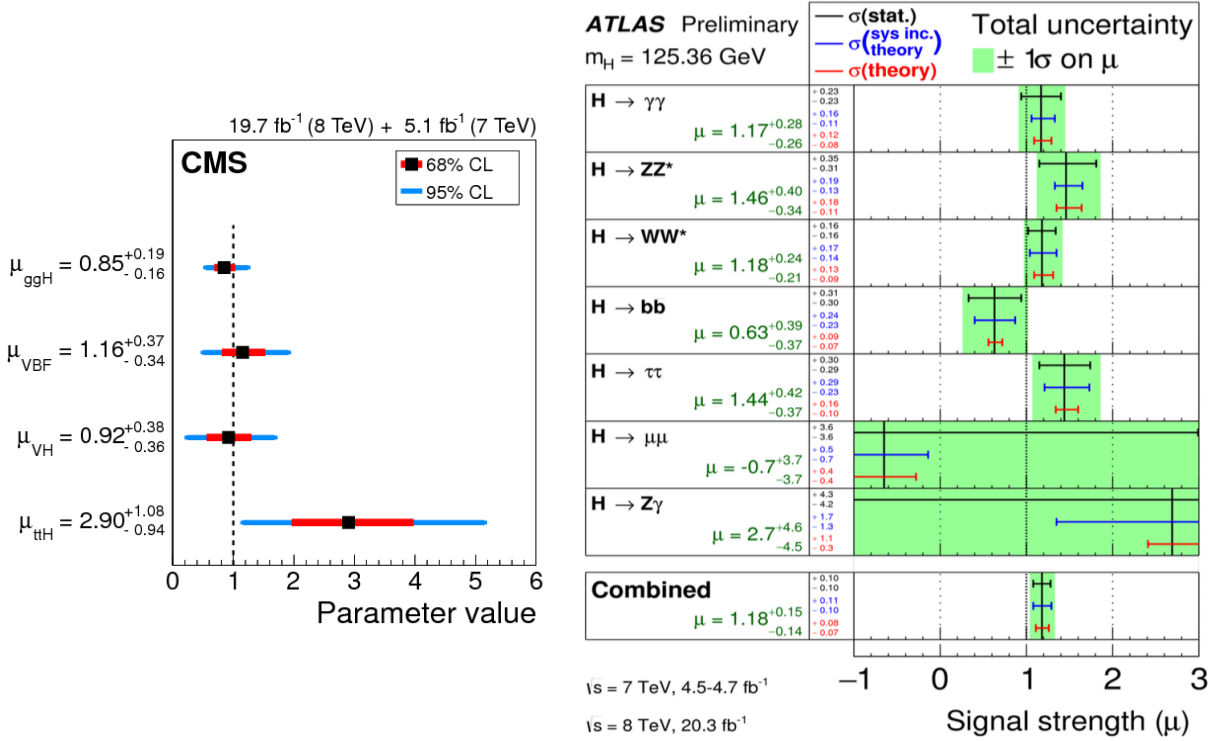


Figure 2 – Left: best signal-strength values, $\mu \equiv \sigma/\sigma_{SM}$, from CMS for different Higgs-boson production channels. Right: best signal-strength values from ATLAS for different decays of the Higgs boson. Figures from talks by Gomez and Peters.^{2,1}

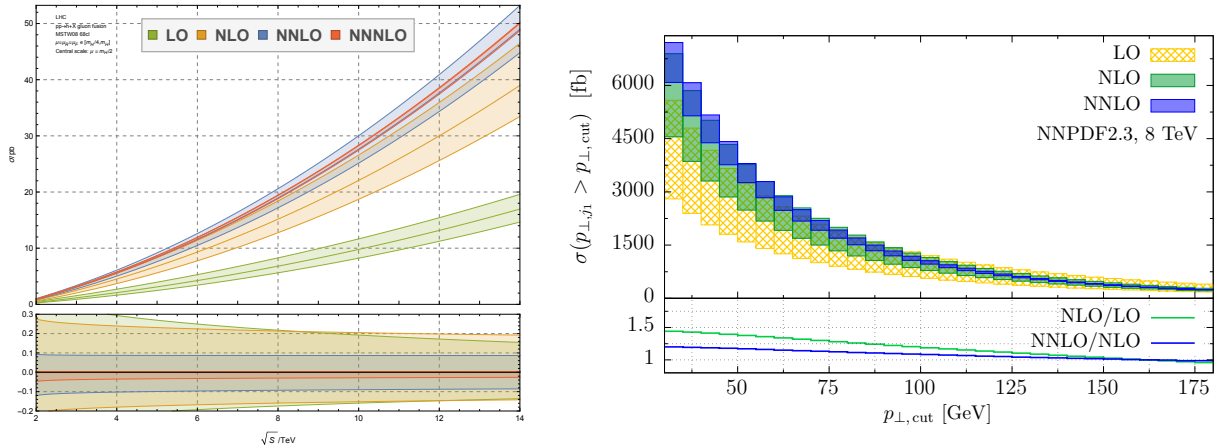


Figure 3 – Left: the Higgs boson total cross section in gluon fusion, as a function of the centre-of-mass energy \sqrt{s} , including the latest NNNLO prediction with its considerably reduced scale uncertainty band (figure⁹ as shown in the talk by Mistlberger⁷). Right: the cross section for a Higgs boson to be produced in association with a jet, as a function of the jet transverse momentum threshold, $p_{T,\text{cut}}$ (figure¹⁰ as shown in the talk by Caola⁸).

For both ATLAS and CMS, there is excellent agreement with the standard-model expectation of $\kappa_F = \kappa_V = 1$, to within 10 – 20% (during the conference only separate ATLAS and CMS fits were available; since then a joint fit has appeared and it is this that is shown in Fig. 1 (right)). Fits of this kind have been carried out using also electroweak precision data. Within certain assumptions as to how a change of κ_V would affect the EW S and T parameters, this would bring further significant reduction in the κ_V uncertainty, to a few percent.⁵

Going forwards, the clear path for the LHC is towards significantly greater precision. Over the course of the next run, the LHC experiments should produce 10 times more Higgs bosons. The resulting factor of three improvement in precision that can be expected from this larger dataset will require significant advances also in our theoretical treatment and predictions. For example, there is much discussion about replacing or supplementing the “ κ -framework” with an effective field theory treatment of possible deviations from the standard model⁶. This would, for example, make it more straightforward to consistently incorporate (large) higher-order QCD corrections in the analysis.

Within the standard-model framework, the large QCD corrections are already critical: the state of the art for the total cross section was until recently next-next-to-leading order (NNLO) in perturbation theory, leading to theory uncertainties from missing higher orders of about 7 – 9%. Such uncertainties are comparable with today’s experimental systematic and statistical errors and so would become the limiting factor for future analyses. Fortunately, there has in recent months been very considerable progress on theoretical calculations: the perturbative uncertainty on the largest Higgs production process, gluon-fusion (in a large top-mass approximation) has been reduced down to about 3% thanks to the first ever NNNLO QCD calculation for a hadron collider process.⁷ Calculations of differential cross sections, notably for Higgs production with an additional jet, have also seen significant advances, and one such result was also presented at this workshop.⁸ Plots illustrating these results are shown in Fig. 3. A number of other calculations of similar complexity have also become available in the past few months.

Interpretations and predictions for hadron colliders involve far more than QCD perturbative calculations, as discussed by Dittmaier:¹¹ electroweak corrections can be crucial, as can re-summations of logarithmically enhanced contributions (e.g. for processes with multiple scales), knowledge of parton distributions (cf. Ref. ¹²), and more-or-less controlled modelling of non-perturbative QCD effects.^b A crucial and very active part of the LHC programme is to test

^bIn some cases one may also gain insight into non-perturbative effects through dualities; such methods were discussed by Son¹³ in the context of condensed matter physics, where they have seen extensive study in the past

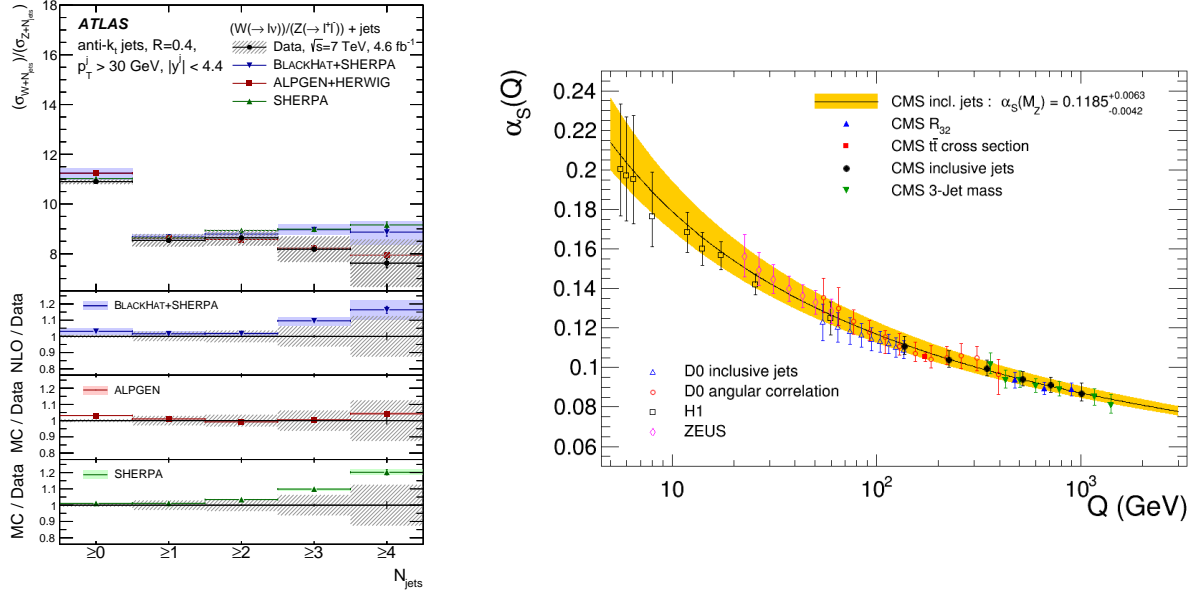


Figure 4 – Left: illustration of the comparison between theory predictions and ATLAS data for the W and Z cross section ratios, as a function of the number of jets (figure¹⁵ as shown in the talk by Savin¹⁴). Right: extractions of the strong coupling over a wide range of scales Q , from CMS and other experiments (taken from the talk by Savin¹⁴).

and further understand this rich panoply of physics.¹⁴ While agreement is usually good (Fig. 4), there are some places with moderate disagreement, typically at the 10–20% level. Further study of these regions of disagreement will undoubtedly help drive progress in our understanding hadron-collider physics.

Among the range of physics processes being studied at the LHC, those involving top quarks have a special place.³ For example, the top is unique in having a Yukawa coupling close to 1, and it decays before hadronisation. Various scenarios of new physics assign a special role to the top quark itself or to partners of the top quark (e.g. a stop squark) and top-quarks then inevitably find their way into new-particle decays. More annoyingly, standard-model top production is a major background to many processes of interest.

Until recently only four experiments had ever observed top-quark production: CDF, D0, ATLAS and CMS. This Rencontres de Blois saw the first conference presentation of results by the LHCb collaboration, showing that they too have now joined the exclusive club of experiments that can study the top, with observation at just over 5σ significance,¹⁶ cf. Fig. 5 (left). LHCb studies a complementary kinematic regime relative to ATLAS and CMS, forward instead of central, and this complementarity is likely to considerably enrich LHC top studies in the years to come.

I commented above on the fact that our knowledge of the Higgs mass already surpasses that of the top mass, cf. Fig. 5 (right), even though top quarks have been studied for the past 20 years (and Higgs couplings are known with an accuracy approaching that of the main top “coupling”, V_{tb}). There are many reasons for this, including the fact that the top quark has no purely photonic or leptonic decays, and the complications associated with the fact that it is a coloured object that decays before it hadronises. However, thanks to its (relatively) large production cross section, there are other aspects where top-quark studies clearly surpass today’s Higgs studies. This is especially the case for differential distributions, which extend up to the TeV scale, both in “standard-model” studies (which show reasonable consistency, albeit with some tension for the the top-quark transverse momentum distribution) and in searches, with sensitivity to new resonances approaching 2 TeV.

few years.

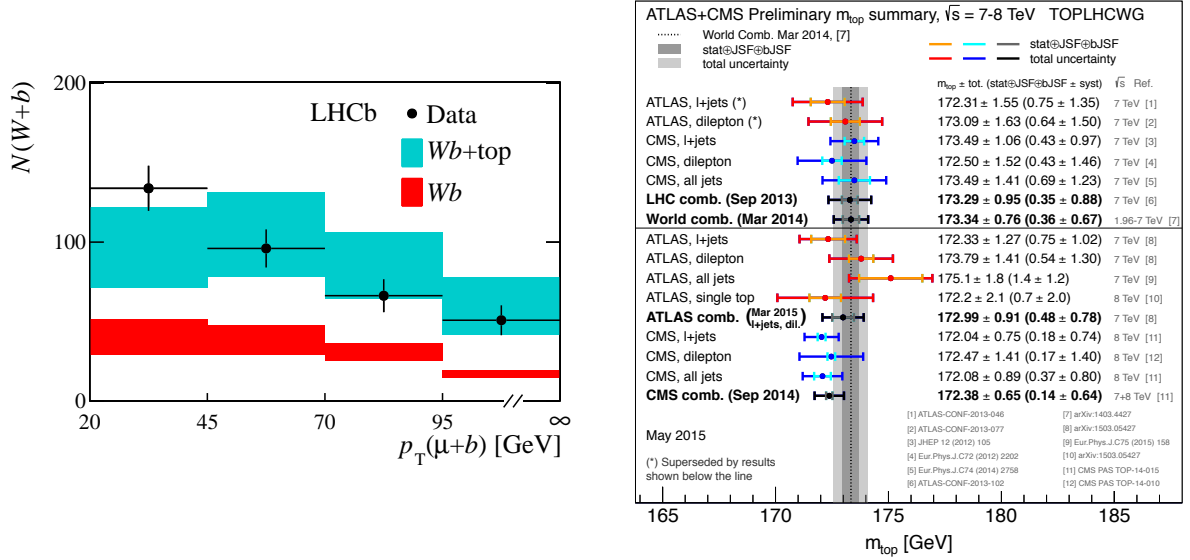


Figure 5 – Left: results from the LHCb experiment showing observation of top quarks (figure as shown by Barter^{16,17}). Right: summary of top-mass measurements at the LHC (figure shown by Lister³).

3 LHC new-physics searches

This naturally brings us to the question of new-physics searches. It is widely believed that elementary scalars are quadratically sensitive to physics at higher scales. Gravity attests to the presence of a higher scale and it seems difficult to ensure that a fundamental massless scalar like the Higgs remains at the electroweak scale without the presence of some new physics nearby,^c as illustrated also in a flowchart, Fig. 6 (left), by Craig.¹⁸

The most extensively studied candidate for physics beyond the standard model is undoubtedly supersymmetry (SUSY), with Fig. 6 (right) illustrating the many topologies in which it might be discovered. As emphasised by various speakers, there are many arguments in its favour such as naturalness, the fact that it provides a candidate for dark matter, unification of the couplings, consistency with the Higgs mass and so forth. Yet, it is common to hear that simplest versions are now excluded up to a mass scale of about 1.5 TeV, which in itself brings a fine tuning of about 1%.

That headline figure perhaps obscures the fact that SUSY is not a theory with a uniquely predicted spectrum. There are many SUSY partners to search for and, depending on the way in which supersymmetry is broken, a range of possible mass spectra. As a result, experimentally, SUSY searches get broken up into very many channels.¹⁹ While some “headline” limits, notably on (degenerate) squarks and gluinos, approach 1.5 TeV, the limit on stop squarks is instead in the range 600 – 700 GeV, while those for electroweak SUSY partners can be even lower, cf. Fig. 7 (left).

Searches for scenarios other than SUSY generally get classified as “exotic” searches. This encompasses a range of new particles and phenomena such as heavy gauge bosons (not so exotic!), leptoquarks, excited fermions, large extra dimensions, RS gravitons, compositeness, various dark matter candidates, etc., as illustrated in Fig. 7 (right).²⁰ One class of searches that I will highlight is that for displaced jets, produced by decays of (relatively) long-lived new particles. Between them, ATLAS and CMS have managed to look jets originating anywhere between a few millimetres from the collision point, all the way up to several metres. Such searches were certainly not the main focus of the original design of the LHC experiments, and the fact that they have been carried out so successfully is a tribute to the ingenuity of the

^cOr nearly thirty orders of magnitude of fine tuning, possibly anthropically driven.

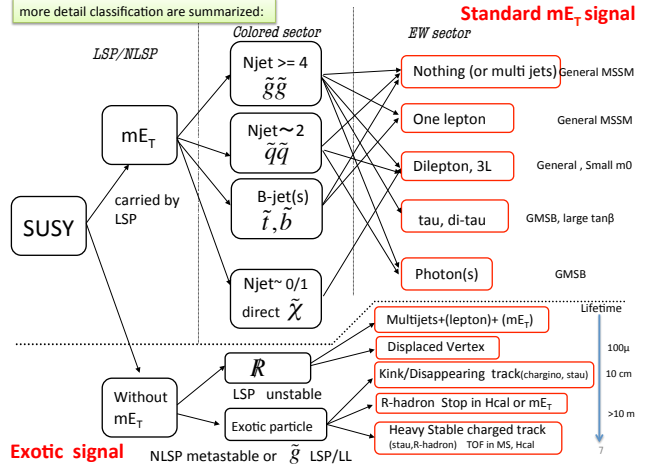
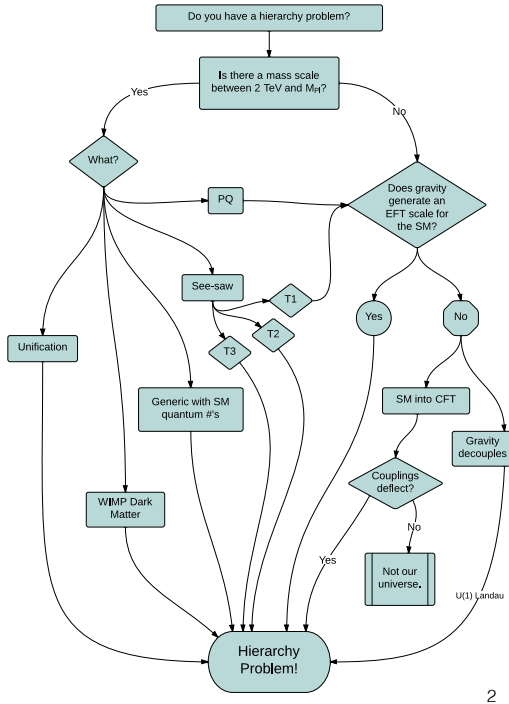


Figure 6 – Left: flowchart illustrating difficulties in evading the hierarchy problem without new physics near the electroweak scale (taken from talk by Craig¹⁸). Right: breakdown of different search strategies for supersymmetry at the LHC (taken from talk by Asai¹⁹).

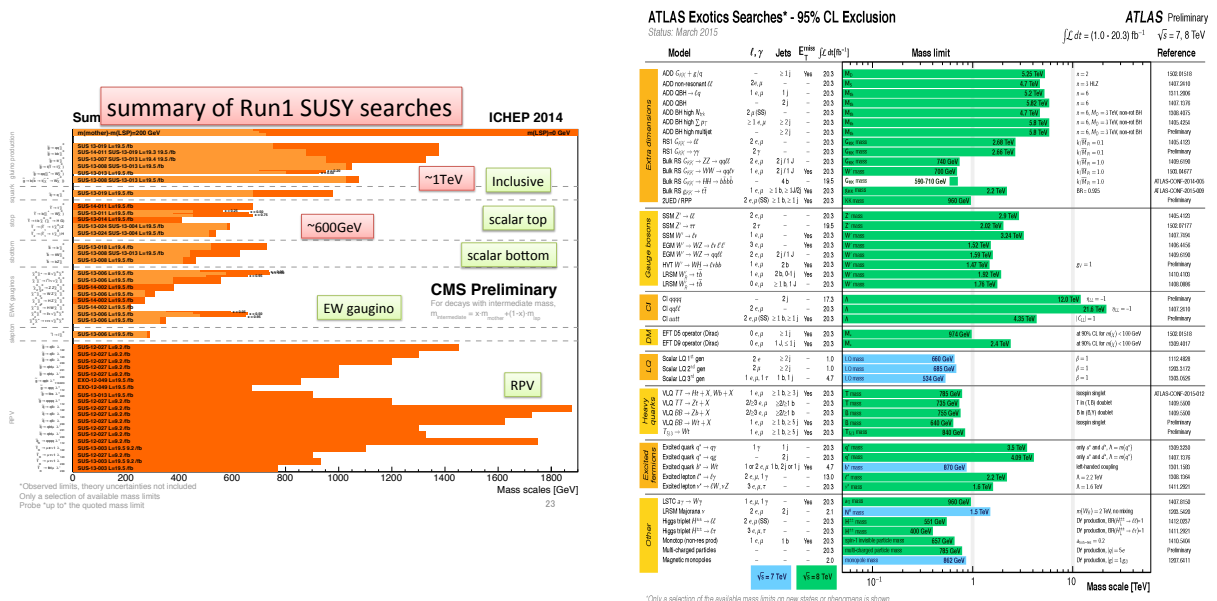


Figure 7 – Limits on new particle masses in SUSY searches (taken from talk by Asai¹⁹) and “exotics” searches (taken from talk by Alcaraz²⁰).

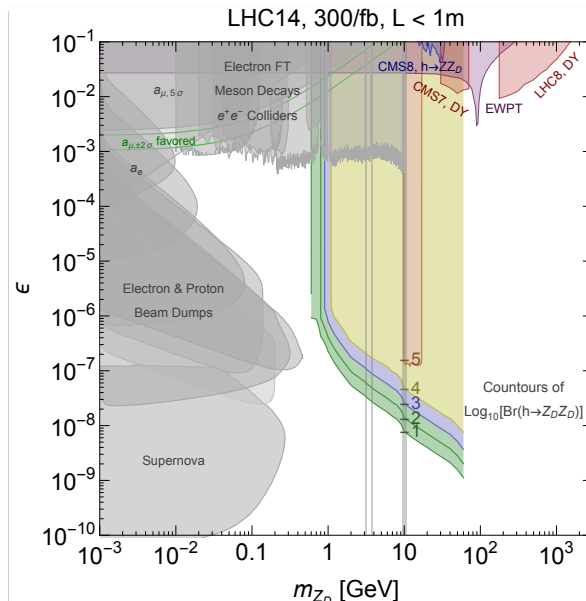


Figure 8 – The LHC’s potential for searches for Z_D dark bosons using (possibly displaced) decays of Higgs bosons (figure taken from the talk by Shelton²¹).

experiments in triggering and exploiting their detectors.

Another dimension that is opening up for searches involves the use of the Higgs boson. As emphasised by Shelton,²¹ one of the respects in which the Higgs is special is its very narrow width, about 4.1 MeV. This is to be compared to the 1 – 2 GeV width of all other electroweak-scale particles. A consequence of the narrow width is that new light degrees of freedom with even only a tiny coupling to the Higgs can still be present in appreciable fractions among its decays. One example involved a Higgs decaying to two dark Z bosons (Z_D), which mix with the electroweak sector to then decay to leptons. The potential coverage from LHC searches is huge and very complementary to other search approaches, as illustrated in Fig. 8.

While the LHC experiments have searched for very many scenarios of new physics, it is impossible for them to cover all possible theoretical models, let alone models that are proposed after a given search is complete. In contrast with astronomy, cosmic-ray and cosmology experiments, the LHC data are generally not public: the largest release of data comes from CMS, and involves about 0.2% of their dataset.²² There are various reasons for this, connected both with the traditions of high-energy physics and the considerable complexity of the raw data: a correct analysis even of the 0.2% of public CMS data is, for an outsider, almost certainly not a trivial enterprise. Consequently, when someone proposes a new model, they cannot simply compare it to data to see if it has already been excluded. Instead it has become standard to adopt a “recasting” procedure:²³ for a given new model A, one identifies existing LHC searches for another model (say B) with similar signatures; one then generates Monte Carlo simulated events for model A, and applies the same cuts that had been used to search for B (including detector smearing and inefficiencies) and sees how many events from model A would survive those cuts. If that number is larger than the upper limit on the number of allowed events in model B, then one can deduce that model A has been excluded. Recasting appears to be a very powerful way to preserve the legacy of LHC’s searches.^d Currently it is mostly being carried out by small groups of theorists, with a few attempts ongoing to systematically recast a large number of the LHC results. In the long term, however, it is unclear whether any single small group can keep pace with the many searches coming from the LHC over its lifetime. How best to scale and sustain the effort needed for generalised recasting remains an open question for the

^dThough there will always be some questions that can only be answered by a full reanalysis of the data.

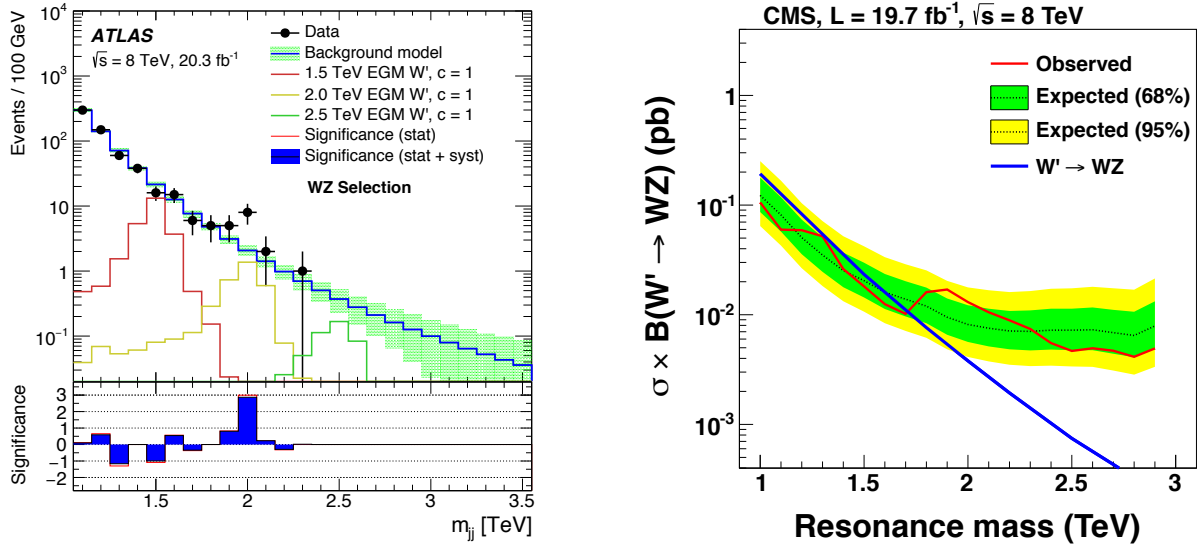


Figure 9 – Results on the searches for diboson resonances in fully hadronic decay channels. Left, the number of events observed by ATLAS as a function of the dijet mass, with two W/Z-boson tags,²⁴ displaying a prominent bump around 2 TeV. Right, the upper limit on the cross section $W' \rightarrow WZ$ from CMS,²⁵ also showing an excess close to 2 TeV.

field.

It would be impossible to close the section on searches without asking whether there are any hints of new physics lurking in the existing data. The general answer is that while there are some discrepancies, there is nothing compelling. One example is in a channel with missing transverse momentum, jets and two leptons (consistent with the Z mass), where ATLAS observes a 3σ excess in the electron channel and 1.7σ in the muon channel. CMS however does not see an excess in the same place. Another example (which has generated considerable theoretical speculation since it appeared) is the search for a resonance decaying to two vector bosons, where both ATLAS and CMS see hints of bumps around 2 TeV, Fig. 9. In the case of the ATLAS data, in the WZ tagged channel, the excess is 3.4σ locally and 2.5σ globally. The CMS bump is slightly lower in mass than the ATLAS one, with a somewhat lower cross section and significance.

4 LHC Run 2 (and beyond)

As the conference was proceeding, the LHC was gearing up for the physics of Run 2, and first 13 TeV collisions with stable beams took place midway through the week. Lamont discussed the huge consolidation effort that went into preparing the LHC for 13 TeV collisions.²⁶ He also described some of the challenges that they have encountered during startup, including the re-training of the superconducting magnets, so called “UFOs”, and so forth. One message that emerged from his talk was “this is not bad”: in a project of this magnitude it is normal to encounter some difficulties and so far those difficulties are being successfully handled as they arise. Nevertheless, he cautioned that with 6.5 TeV beams, the machine will be operating much closer to its limits than was the case for 4 TeV beams.

In terms of luminosities, the hope for this year is to obtain between about 4 fb^{-1} (recall Run 1 delivered 20 fb^{-1} at 8 TeV) and 100 fb^{-1} by the end of Run 2. Alcaraz²⁰ used a tool called ColliderReach²⁷ to help illustrate when 13 TeV data will start to become competitive with 8 TeV results. In searches involving large system masses, say around 4 TeV (e.g. the current limit for excited quarks), just 0.1 fb^{-1} will be sufficient. At lower masses, say 1 TeV, one needs about 5 fb^{-1} to overtake the Run 1 results.

To look further into the future, it is instructive to take a simple, concrete example, say a

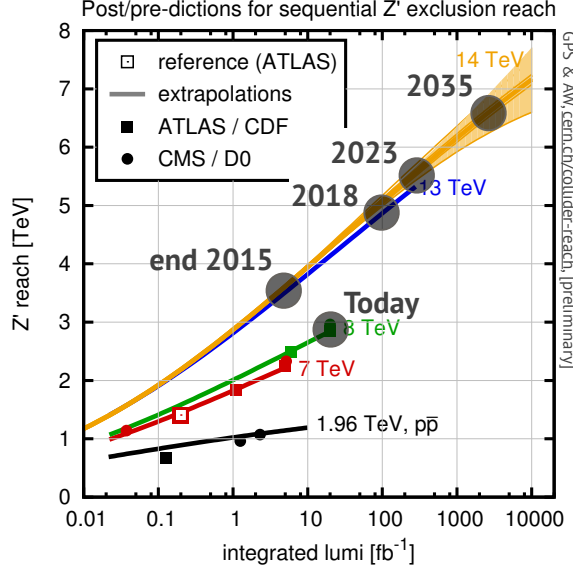


Figure 10 – Post- and predictions for the Z' search (exclusion) sensitivity, as a function of luminosity, for different collider setups and centre-of-mass energies.²⁷ The (post)prediction is based on the momentum dependence of partonic luminosities. Key luminosity targets for the LHC programme are highlighted together with approximate dates when they should be achieved.

sequential standard model Z' decaying to leptons (Fig. 10). Today the limit is about 2.9 TeV. Using the ColliderReach tool for extrapolations, one can establish that by the end of 2015 with 5 fb^{-1} the limit could go up to 3.6 TeV; by the end of Run 2 in 2018, with 100 fb^{-1} , this should rise to about 5 TeV; Run 3 (300 fb^{-1} , 2023) should take this to 5.4 TeV, while the high-luminosity LHC (3000 fb^{-1} , around 10 years later), will take us to about 6.4 TeV. The details vary depending on the precise search, but a common pattern that emerges is that the coming year offers only the very first step towards the ultimate limit of what LHC will be able to probe, even if some patience may be needed on the way towards that limit.

5 (Quark) Flavour Physics

So far, most of the discussion has concentrated on direct probes of scales from a hundred GeV to a few TeV. Yet almost 50% of the conference was dedicated to subjects outside this direct range of scales. Experimentally, quark flavour physics mostly involves scales of a few GeV. A huge effort from the flavour experiments (and also the lattice QCD community) has led to multiply constrained determinations of the different elements of the CKM matrix, with a generally consistent picture emerging from many different measurements, cf. Fig. 11 (left). Some points of tension do persist, and in his review talk Gershon²⁸ highlighted the difference between V_{ub} extractions from inclusive B -meson decays and exclusive decays. A new addition to this story was recent LHCb data on V_{ub} from exclusive decays of B -baryons, which is very consistent with that from the exclusive meson decays. Another place of tension is in lepton universality with the observed ratio of $(B \rightarrow D^{(*)} \tau \nu) / (B \rightarrow D^{(*)} \mu \nu)$ decays being $3 - 4\sigma$ higher than expected in the standard model, a finding that has been reinforced by recent LHCb data.²⁹

As well as determining the CKM matrix (and verifying the consistency of different determinations) an important aspect of flavour physics is the study of rare decays. The $B_s \rightarrow \mu^+ \mu^-$ is one decay that is of particular interest because it is highly suppressed in the standard model, while it may be enhanced in new-physics models. This is similar to the argument, given above, about Higgs decays being especially interesting places to search for new physics, because of the narrow width of the Higgs boson. The $B_s \rightarrow \mu^+ \mu^-$ branching ratio has recently been measured, jointly by CMS and LHCb,³¹ to be about $3 \times 10^{-9} \pm 20\%$, consistent with the standard

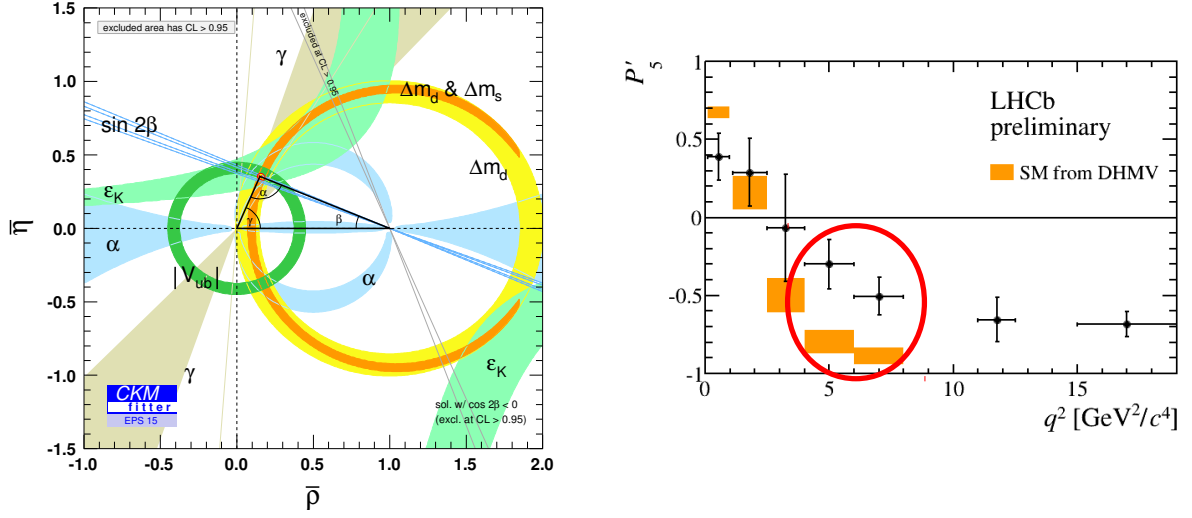


Figure 11 – Left: status of constraints on the CKM matrix (plot as shown in the talk by Gershon,²⁸ taken from Ref.³⁰). Right: the distribution of the P'_5 angular observable in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays, as a function of the momentum scale q^2 , highlighting the discrepancy around 5 GeV^2 (figure taken from talk by Gershon²⁸).

model. Haisch, in his review,³² made several comparisons with Higgs physics: the experimental precision $B_s \rightarrow \mu^+ \mu^-$ branching ratio is comparable to that on Higgs production and decay; what's more if one tries to deduce a limit on the scale of new physics based on the observed consistency with the standard model, one reaches conclusions that are similar, just below a TeV (in the case of $B_s \rightarrow \mu^+ \mu^-$ the limit becomes much higher if one relaxes the assumption that new physics has a flavour structure aligned with that of the standard model, i.e. minimal flavour violation).

One point of tension in rare decays that is currently the subject of much attention is the so-called P'_5 angular observable in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays,^{28,33} Fig. 11 (right). There was some discussion³² however as to the degree of robustness of the theoretical predictions for this observable.

The difficulties that arise in interpretations of hadronic physics were discussed also in the context of studies of hadronic resonances that are candidates for being four-quark bound states.³⁴ In the future it may be possible to obtain complementary probes of anomalies in the quark sector using high-momentum-transfer processes, and one in particular that was highlighted was $t\bar{t}Z$ production.³⁵

6 Neutrinos and the lepton sector

The neutrino sector of particle physics is special in that a number of the important unanswered questions should be clearly resolvable in the coming decade. The state of today's knowledge^{36,37} is that we have reasonable constraints on the absolute values of the neutrino mixing matrix V_{PMNS}

$$V_{\text{PMNS}} \simeq \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}, \quad V_{\text{CKM}} \simeq \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}, \quad (1)$$

here compared to the absolute values for the corresponding quark mixing matrix V_{CKM} , and illustrating the much greater mixing in the neutrino sector. There are 2σ hints for a large CP-violating phase, Fig. 12, whose value could be of importance for understanding the origin of the baryon asymmetry of the universe.

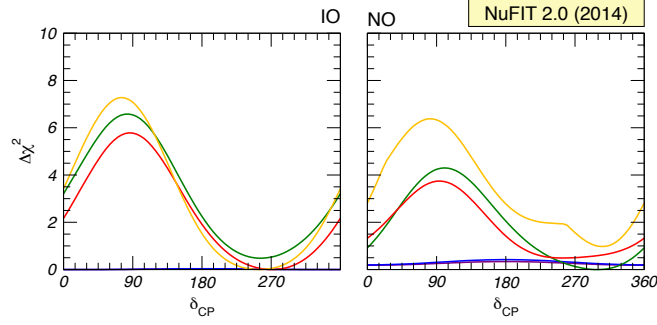


Figure 12 – NuFIT results showing a 2σ hint for a CP phase around $\delta_{\text{CP}} = \frac{3\pi}{2}$. Taken from the talk by Gonzalez-Garcia.³⁶

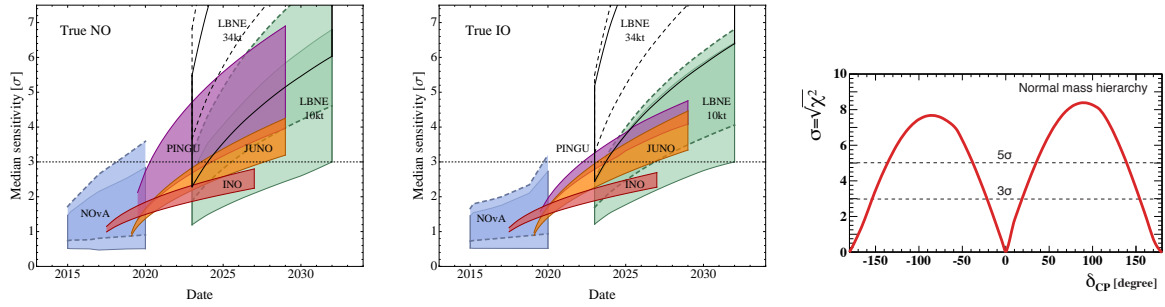


Figure 13 – Left and middle: timeline for the expected range of significances for the determination of the mass ordering hierarchy of the neutrino sector, illustrating the different contributing experiments in both a normal (left) and inverted (middle) hierarchy.³⁹ Right: expected significance on the CP-violating phase δ_{CP} from the Hyper-Kamiokande experiment, as a function of δ_{CP} .⁴⁰

Regarding neutrino masses, there are bounds from β -decay experiments on the electron neutrino mass, $m_{\nu_e} < 2.2 \text{ eV}$. Bounds from cosmology depend on the specific cosmological observables being considered, but can be as strong as $\sum m_\nu \lesssim 0.17 \text{ eV}$ on the sum of neutrino masses. Oscillations provide information on mass differences: $\delta m_{12}^2 \simeq 7 \times 10^{-5} \text{ eV}^2$ and $|\delta m_{23}^2| \simeq 2 \times 10^{-3} \text{ eV}^2$. The sign of δm_{23}^2 is however not known, so the problem of determining the mass hierarchy remains open. It is also not known whether neutrinos are Majorana or Dirac fermions.

One new result presented at this conference concerned the observation of $\bar{\nu}_\mu$ disappearance by T2K.³⁸ The results are compatible with those for ν_μ disappearance, as should be the case assuming CPT symmetry. To make progress with the determination of the CP-violating phase, it is necessary to observe a difference in the rates of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations. However neutrino-matter interactions also induce such an asymmetry, and the magnitude of this effect depends on the (unknown) neutrino mass hierarchy. To disentangle the two effects requires an appropriate span of neutrino energies and oscillation baseline lengths. An indicative timeline for the evolution of different experiments' sensitivities to the mass hierarchy is shown in Fig. 13, as is the sensitivity to the CP-violating phase that should eventually come, on a 10-year timescale, from the Hyper-Kamiokande experiment (the LBNF/DUNE experiment will also provide similar information).

Regarding the absolute mass scale, progress is expected from the Katrin experiment on the limit on the electron neutrino mass. If neutrinos are Majorana fermions, then there is also a prospect of sensitivity to this in neutrinoless double- β decay experiments in the next decade, notably for an inverted mass hierarchy.^{41,42}

Neutrino-based studies of the lepton sector are complemented by experiments with charged leptons, where substantial improvements, for example in limits on $\mu^+ \rightarrow e^+ e^+ e^-$ decays, are expected in the coming years.⁴³

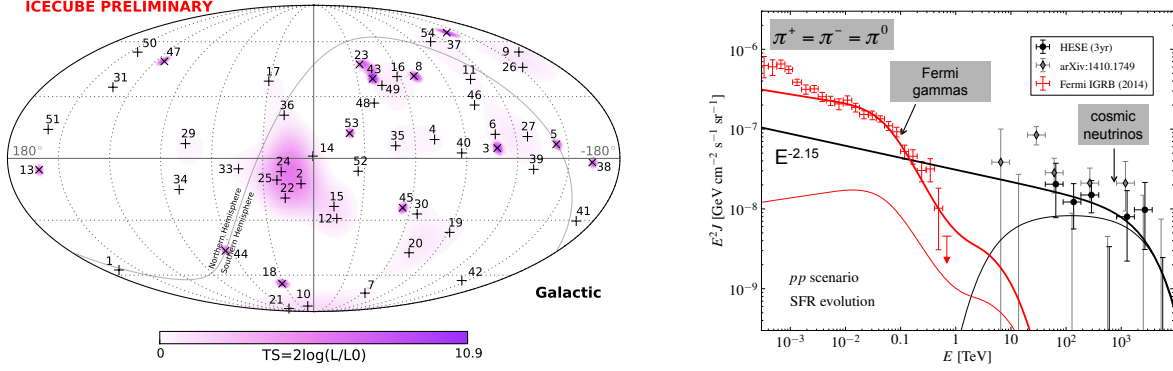


Figure 14 – Left: distribution of neutrinos from the sky as reported by the IceCube experiment; the shading represents a test statistic (TS) for clustering. Right: spectra of photons (in red) and cosmic neutrinos (in black). The thick lines represent an attempt to jointly fit the neutrino and γ ray spectra under the assumption that both arise dominantly from pion decay. Both plots taken from the talk by Halzen.⁴⁴

7 Cosmic Rays

The subject of neutrinos naturally brings us to the question of cosmic rays, where one of the significant advances in recent years has been the observation of astrophysical neutrinos by the IceCube detector, as presented by Halzen.⁴⁴ The importance of neutrinos is that like photons, but unlike charged cosmic rays, their direction of arrival points back to the source; furthermore, in contrast to photons, they undergo essentially no absorption or scattering as they travel to us.

The full set of astrophysical neutrino candidates is shown in Fig. 14 (left). Initial two-year data appeared to have an excess coming from the galactic centre, however in the latest four-year results the significance of that excess has gone down. Currently there is no evidence for any other clustering within the neutrino dataset.^e To reliably observe multiple neutrinos from any single astrophysical sources, it is expected that a 10 km^3 detector volume would be sufficient. Remarkably, the antarctic ice is sufficiently transparent that such a detector could be successfully instrumented with the same number of “strings” as currently used for the 1 km^3 volume of IceCube.

Halzen also showed a quantitative comparison of the observed neutrino flux with the gamma-ray flux. The basis of the comparison is that a main expected source of neutrinos is π^\pm decays with the pions themselves being produced for example in collisions of energetic protons with some kind of target (e.g. gas). In that case energetic photons should be produced at a similar rate in π^0 decays. However very energetic photons will then interact with the cosmic microwave background (CMB), leading to a degradation of their energy. The observed neutrino flux can therefore be used to infer a flux of pion-decay induced gamma-rays, which, remarkably, coincides well with the high-energy part of the observed Fermi gamma-ray spectrum, Fig. 14 (right). This would suggest that it is production of pions in astrophysical accelerators that is responsible for most of the photon flux.

The origin of energetic gamma rays was discussed also by Funk.⁴⁵ He observed that if very high energy photons are being produced in π^0 decays, then there should be a dip in the spectrum around $m_\pi/2$. Fig. 15 shows that such a dip does indeed seem to be present in data from Fermi-LAT.

Despite these hints about the origin of high-energy photons, much remains to be understood as to how, precisely, cosmic rays are accelerated to the very high energies that are observed. Most probably, this occurs in shocks in supernova remnants, but there is as yet no observational proof.⁴⁸ Still, even if such proof is lacking, there is considerable progress in learning at least about the composition of cosmic rays. At the very highest energies, up to $\sim 10^{19} \text{ eV}$, Roth⁴⁶

^eStudies of correlations to catalogues of known sources is currently ongoing.

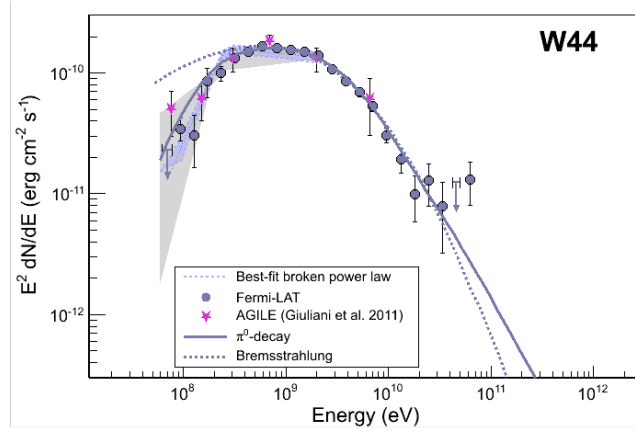


Figure 15 – Photon spectrum from the W44 supernova remnant, compared to various models, including one in which the photons originate from π^0 decay. Plot taken from talk by Funk.⁴⁵

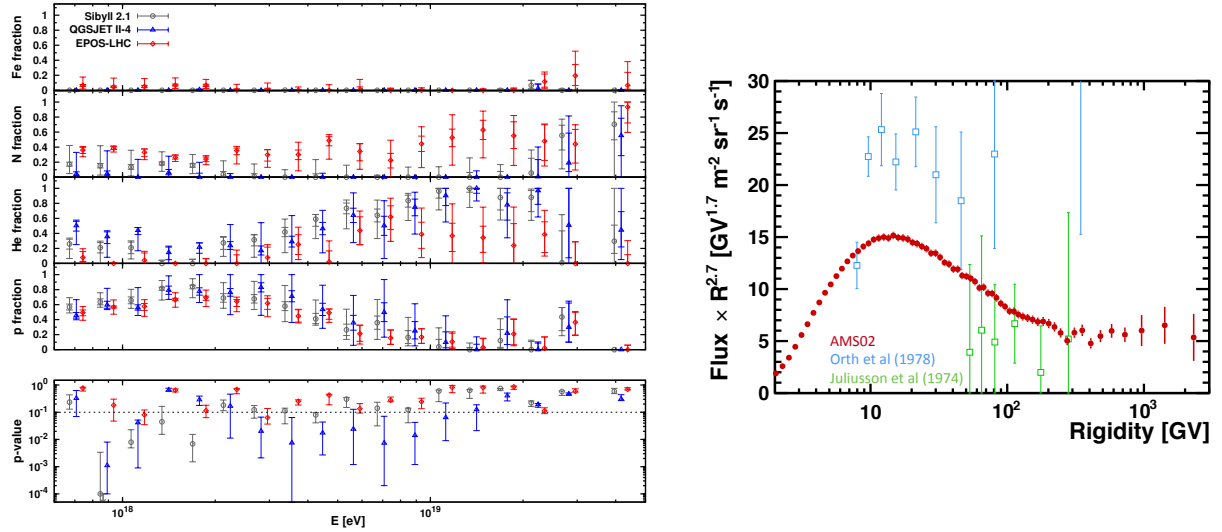


Figure 16 – Left: fits for the nuclear composition of cosmic rays, based on the depth of the maximum of the cosmic ray shower, shown as a function of different energies, with various Monte Carlo programs used to model the shower development; taken from talk by Roth.⁴⁶ Right: cosmic Lithium flux, shown as a function of “rigidity” (p/Z where p is the momentum) as measured by the AMS collaboration; taken from the talk by Derome.⁴⁷

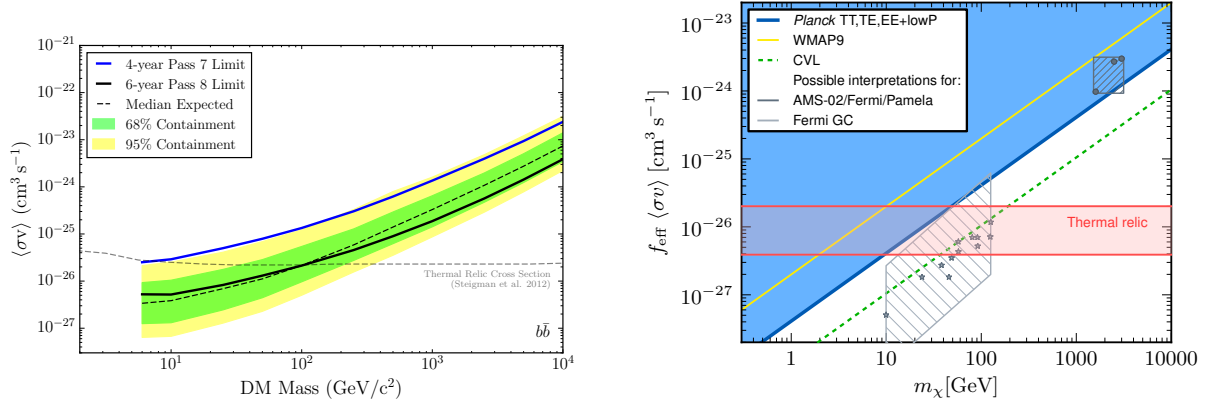


Figure 17 – Left: Fermi-LAT 95% confidence level constraints on the dark-matter annihilation cross section to $b\bar{b}$,⁴⁹ compared to a calculation of the thermal relic cross section.⁵⁰ Right: Planck limits on the dark-matter annihilation cross section as obtained from the structure of CMB.⁵¹

presented results from Auger on the fraction of protons, helium, nitrogen and iron, Fig. 16 (left). At lower energies, up to about 1 TeV, we saw beautifully precise data on the fluxes of various nuclei as measured by the AMS experiment,⁴⁷ e.g. Fig. 16 (right).

8 Dark Matter

As well as being of intrinsic interest as a window on the astrophysical mechanisms at play in the universe, cosmic rays offer the prospect of indirect detection of dark matter. Given some dark matter particle χ , one can for example imagine annihilations $\chi\chi \rightarrow W^+W^-, ZZ, q\bar{q}$, etc., all of which would result in a continuum distribution of protons, photons and electrons that turns off somewhere below m_χ . There is also the possibility of annihilation such as $\chi\chi \rightarrow \gamma\gamma$, which would give a distinct line signal in the γ -ray spectrum.

Strigari⁵² reviewed recent results on indirect dark matter detection. In particular, the Fermi-LAT collaboration has combined upper limits on gamma ray rates from Milky Way dwarf spheroidal satellite galaxies (dSphs) with information about the satellites' dark matter mass, in order to place constraints on the annihilation cross section for various channels. The constraints on one specific channel, $\chi\chi \rightarrow b\bar{b}$, are illustrated in Fig. 17. They are compared to the cross section that is required to obtain the right thermal relic density and one sees that the resulting limit on the DM particle mass, $m_\chi \gtrsim 100$ GeV, is in the same ballpark as scales that are being probed at the LHC.

Limits on annihilation cross sections are also being placed by Planck data on the CMB, since annihilation products would inject energy into the gaseous background, modifying the CMB peaks. Those limits, shown in Fig. 17 (right) depend only moderately on the annihilation channel, through a factor f_{eff} that encodes the fraction of rest-mass energy that is injected into the gaseous background. The resulting lower limits on the mass of the dark-matter particle are at the level of a few tens of GeV.

One source of potential hints about dark matter in recent years has come from an observed increase in the fraction of positrons relative to electrons with increasing energy and also of the fraction of anti-protons relative to protons. Such increases would be expected at energies in the vicinity of the mass of dark-matter particle. The increases have been confirmed by recently released data from the AMS experiment.⁴⁷ However there can also be astrophysical explanations (e.g., in the case of positrons, involving pulsars and supernova remnants) for such an increase, and it appears to be difficult to distinguish between different explanations, cf. Fig. 18.

One excess that has yet to find well-fitting astrophysical explanations was discussed by Linden.⁵⁶ This is an excess in gamma-rays, peaked around 2 GeV, originating from the galactic

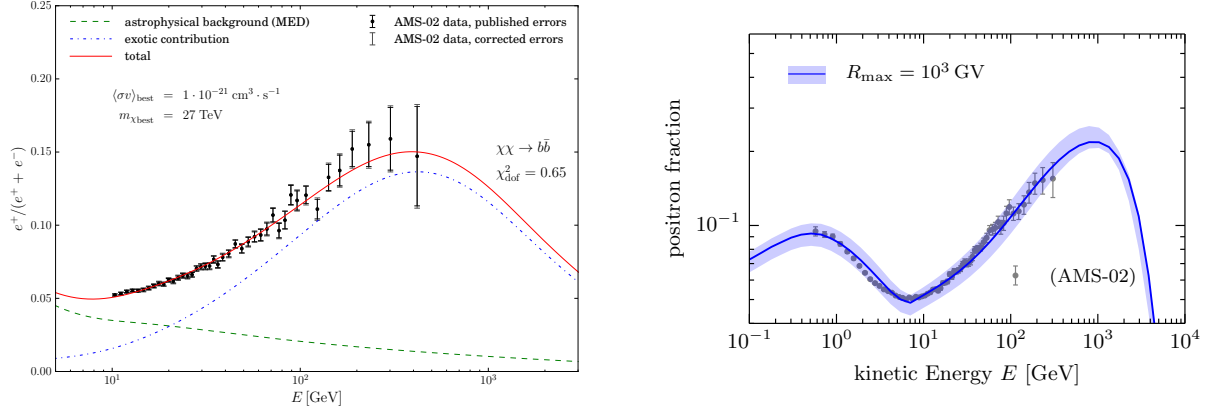


Figure 18 – Left: fit to the AMS data on the positron fraction, shown as a function of energy, including a component from dark matter annihilation, $\chi\chi \rightarrow b\bar{b}$. Right comparison of the same AMS data to a model for production and acceleration of cosmic rays in supernova remnants. Figures as shown by Derome,⁴⁷ taken from Refs.^{53,54}

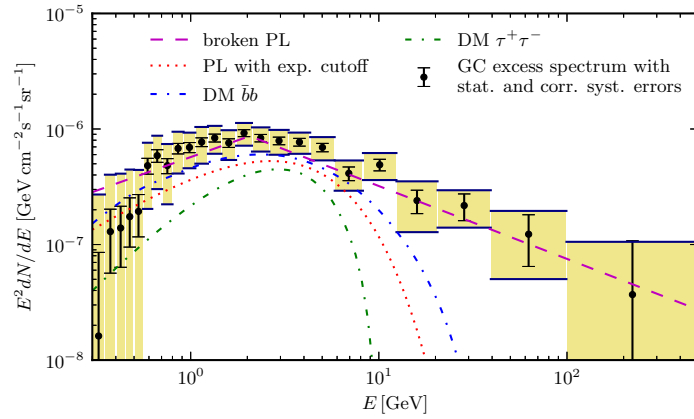


Figure 19 – The excess in the galactic-centre γ -ray spectrum, measured by the Fermi experiment, with comparisons to spectra from illustrative dark-matter models ($\chi\chi \rightarrow b\bar{b}$ with $m_{\chi} = 49 \text{ GeV}$ and $\chi\chi \rightarrow \tau^+\tau^-$ with $m_{\chi} = 10 \text{ GeV}$) and modifications of simple power laws (PL).⁵⁵ Figure as shown in the talk by Linden.⁵⁶

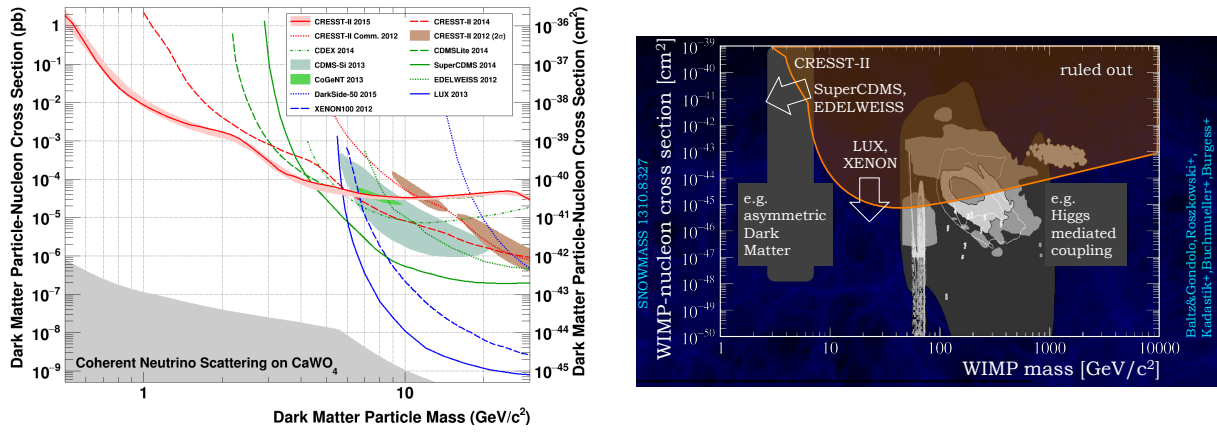


Figure 20 – Left: current limits from direct dark matter searches, as shown in the talk by Cerdeño.⁵⁷ (Figure taken from Ref. ⁶⁰). Right: comparison of today's limits with the dark-matter mass and nucleon coupling from the parameter space of various models. (Figure taken from Lang's talk.⁶¹)

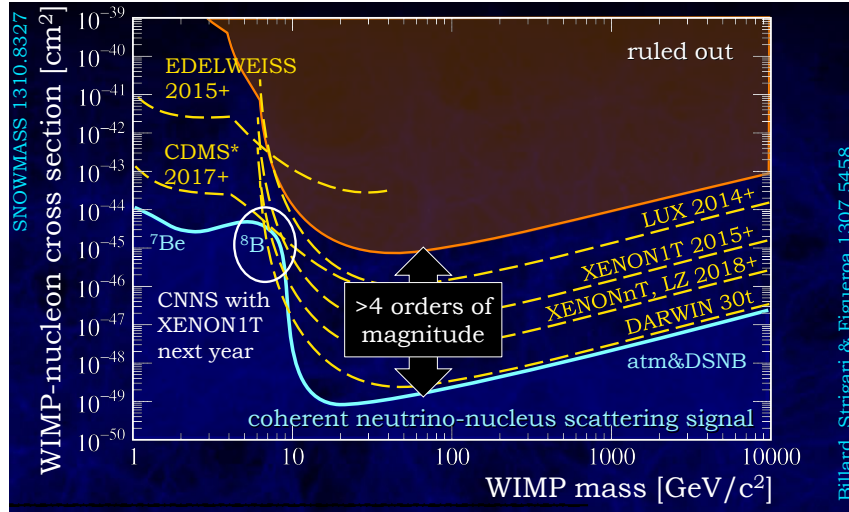


Figure 21 – Prospects for dark-matter searches as shown in the talk by Lang.⁶¹

centre (but also up to 10° away), with the spectrum shown in Fig. 19. It was stated that it is very resilient to changes in the background modelling, for example with a spectrum harder than expected for astrophysical pion emission. Dark-matter interpretations generally involve particle masses in the range of $10 - 40 \text{ GeV}$.⁵⁷ One of the key questions for future observations will be whether this excess is found to be present also in other regions of dark matter concentration, notably in dwarf galaxies.

The ideal indirect dark-matter detection signal would of course be an excess of gamma rays at a very specific energy, i.e. a sharp line feature. One such feature had been claimed around 133 GeV ,⁵⁸ however with the most recent Fermi-LAT data the signal appears to have largely disappeared.⁵⁹

Dark matter is also being searched for through direct detection experiments, which most commonly look for evidence of nuclei recoiling after a coherent elastic interaction with a dark-matter particle. While there have been various excesses over the years, at least one of which still remains unexplained, overall the picture is largely one of exclusion limits. The current status of the limits for the WIMP-nucleon cross section v. WIMP mass is shown in Fig. 20, including also a plot of expected cross section and mass values in a range of models. One should be aware that such a figure comes with numerous assumptions: that of an isothermal spherical halo, dark matter with only spin-independent interactions, a coupling to protons that is

similar to that to neutrons, and that the scattering would be elastic.⁵⁷ Within these assumptions, progress has been remarkable, with Lang⁶¹ pointing out that cross-section sensitivity has been doubling every year for the past several years. Rapid progress is expected to continue for a number of years still: for masses above 10 GeV, there are about 4 orders of magnitude in cross section between current limits and the coherent neutrino-nucleus scattering signal expected from atmospheric neutrinos and the diffuse supernova neutrino background, and there is a well-defined programme of experiments that should eventually be able to reach that limit. There are also impressive prospects for progress in sensitivity to masses in the few-GeV range, with many orders of magnitude improvement in cross-section sensitivity expected from Edelweiss's 2015 data and CDMS around 2017. Meanwhile, in the region of sensitivity to masses around 10 GeV, where the ^8B solar-neutrino background is particularly strong, one may expect observation of those neutrinos in XENON1T already next year.

One interesting point of comparison between LHC physics and direct dark-matter detection (aside from the fact that they may both look for the same models) is the increasing use of effective theories: these are under much discussion for constraining Higgs properties⁶ and are being examined also for dark matter searches, as discussed by Cerdeño,⁵⁷ where they help to systematically identify the very important complementarity between different detector materials in terms of sensitivity to different operators. Such information may play an important role in guiding the design of future direct detection experiments.

9 Cosmology

There are many questions that cosmology may help us solve: for particle physicists, it can bring insight into questions such as dark matter annihilation or neutrino masses, and it of course also brings insight into questions that are more directly cosmological, e.g. the fundamental characteristics of inflation and dark energy.

Ensslin's talk⁶² summarised some of the amazing array of results from Planck. One result that had been particularly awaited was the joint Planck and BICEP/Keck analysis of the ratio of tensor to scalar perturbations, r . The reader almost certainly does not need reminding about the excitement over BICEP/Keck's earlier apparent observation of a non-zero r , which offered the hope of bringing detailed insight into some of the physics at play in inflation. The latest analysis involved a more robust separation of three components: the intrinsic tensor perturbations, the contributions from dust and those from synchrotron radiation. Ultimately, as is now well known, the data no longer point to the presence of tensor perturbations, but instead just place an upper limit on their magnitude, as illustrated in Fig. 22. Future prospects for improvements were discussed in the talk by Ahmed.⁶³

Another potential source of insight into the physics of inflation would be the observation of primordial non-Gaussianity (PNG) in the spectrum of scalar perturbations. As discussed by Peiris,⁶⁴ one can obtain limits on PNG from the CMB, for example from 3-point correlations. One could also identify its impact on large scale structure, specifically quasars, sensitive to PNG because it should lead to enhanced clustering of massive objects. Ultimately both methods indicate that any PNG is at best small, Fig. 23.

While the questions of tensor fluctuations and PNG bring may insight into the early universe, another pressing question is that of dark energy, which appears to dominate today's universe. As discussed in Rigault's talk,⁶⁵ it had appeared that there was tension at the 2.5σ level between extractions of the Hubble constant from Planck data and from supernovae. Supernovae are useful because the uniformity of their brightness makes it possible to use them to estimate distances. Rigault presented new results that indicate that type 1A supernovae in star-forming environments are somewhat fainter than other type 1A supernovae. This helps resolve the tension, as illustrated in Fig. 24.

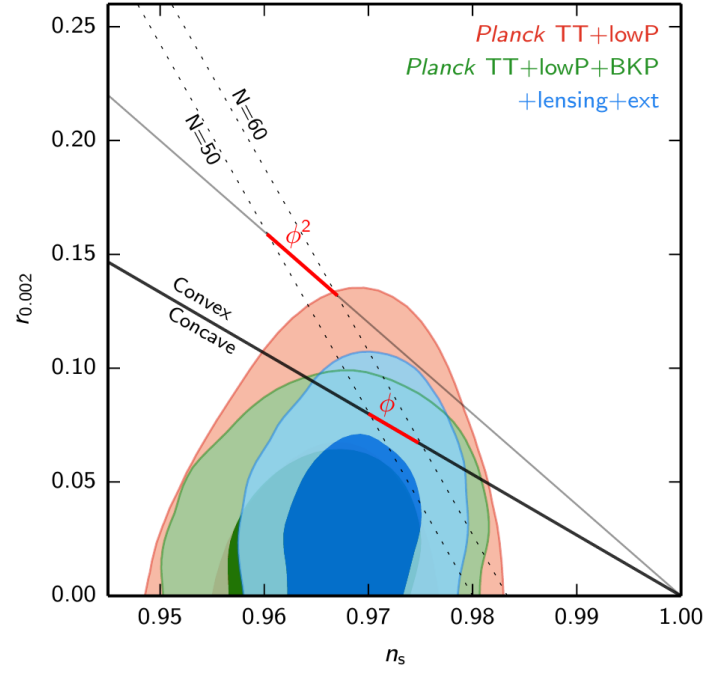


Figure 22 – Results on the limit of tensor to scalar perturbations from the joint analysis of Planck and BICEP-Keck data, shown as a function of the scalar perturbation spectral index n_s (taken from the talk by Ensslin⁶²).

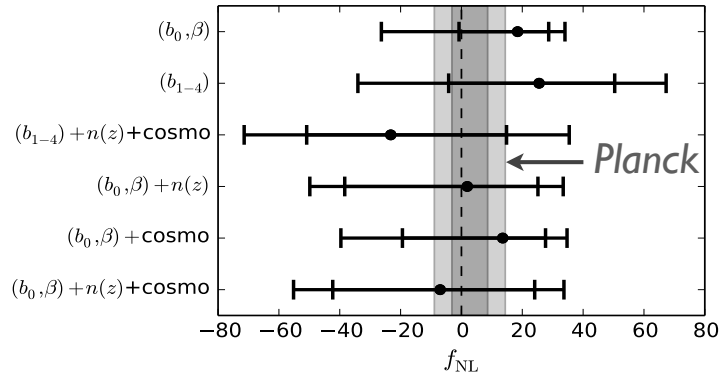


Figure 23 – Limits on the primordial non-Gaussianity parameter f_{NL} as obtained from a variety of methods (taken from the talk by Peiris⁶⁴).

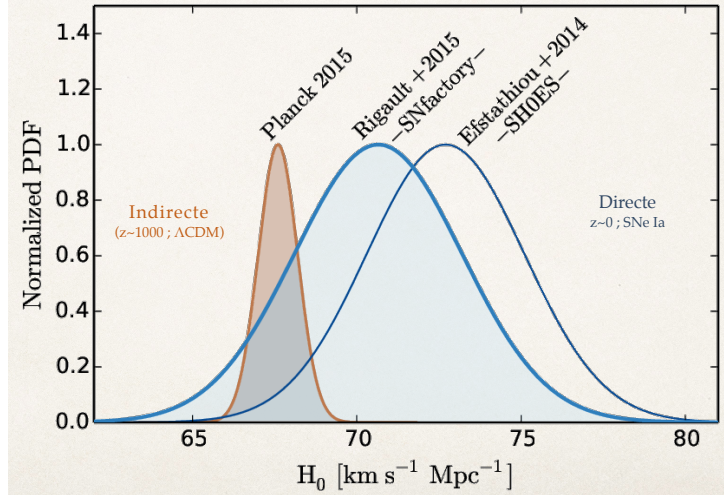


Figure 24 – Extractions of the Hubble constant from Planck and from two supernova studies, one of which (SNfactory) takes into account the impact of environment on the supernova brightness (taken from the talk by Rigault⁶⁵).

10 Concluding remarks

There is some palpable frustration in the fields both of particle physics and cosmology at the lack of confirmed discoveries of physics beyond their respective standard models. This is despite the existence of fundamental open problems, such as the identification of dark matter, gaining insight into the hierarchy between the electroweak and Planck scales, probing the nature of dark energy or understanding the origin of the baryon asymmetry of the universe.

Nevertheless, there is amazing progress in improving experimental sensitivity to new phenomena, as well as in the theory tools that help us interpret the experimental results. In tandem with this progress, we are substantially expanding our knowledge about cosmological and particle physics parameters, including Higgs and neutrino properties. One should also keep in mind the long-term importance of today’s many null searches: in the future when something is discovered, it will in part be because of those null searches that we may be able to narrow down the viable candidates for explaining the discovery.

Even without immediate breakthroughs, there remains much to be learnt and probed about our universe, and it is through that effort of probing, in the broadest range of ways and making the best of the tools that we can design, that we will ultimately be in a position to make whatever discoveries Nature places within our reach.

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